The Majorana Project: A Next-Generation Double-Beta Decay Experiment

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Abstract. The Majorana Project will endeavor to provide direct limits on the effective Majorana mass of the electron neutrino through the measurement of $0\nu\beta\beta$ decay in ^{76}Ge. Our goal is an experiment with a scalable sensitivity starting at 100 meV (corresponding to the quasi-degenerate mass scale) and ultimately extending well below that level. The current Majorana design consists of several modules, each a close-packed array of 57 Ge detectors, enriched to 86% in ^{76}Ge, in a single cryostat. The ultimate background goal for Majorana is of order one count per tonne of Ge per year in the four keV region of interest around $Q_{\beta\beta}$. This background will allow us to reach an effective Majorana-neutrino mass sensitivity approximately five times better than current results and should cover the quasi-degenerate mass scale.

Keywords: Neutrino, Double-Beta Decay, Germanium Detector
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1. INTRODUCTION AND PHYSICS MOTIVATION

The study of neutrinos through $0\nu\beta\beta$ decay is an extremely exciting field of modern nuclear and particle physics with immense discovery potential[1]. We now have a lower bound on the electron neutrino mass scale from the oscillation experiments[2][3][4], and the next step for the community is to increase our neutrino mass sensitivity to approximately 100 meV (assuming light neutrino exchange is dominant mechanism for $0\nu\beta\beta$). To attain this, we require an increase in $0\nu\beta\beta$ lifetime sensitivity of approximately 10 to 100 times over the previous generation of experiments. If $0\nu\beta\beta$ decay exists, it will be an extremely rare decay, and any experiment attempting to observe it would have to have a variety of characteristics well-suited to a large array of ultra-low background Ge detectors enriched in ^{76}Ge (the Ge isotope capable of undergoing $\beta\beta$ decay). First, successful $0\nu\beta\beta$ experiments should have good energy resolution. Better energy resolution not only allows for a narrower region of interest, but also helps to separate the $0\nu\beta\beta$ peak from the broad $2\nu\beta\beta$ continuum. Ge detectors have the best energy resolution of any widely available radiation detector technology, allowing for a region of interest of only 4 keV at $Q_{\beta\beta}$. Also, a next-generation experiment will need a source mass on the order of 100 to 200 kg. Ge detectors can be built in large, close-packed arrays, and while ^{76}Ge has a relatively low natural abundance (7.8%), it has a well-demonstrated enrichment technology. These two characteristics make an active source-style experiment eminently practical. Any successful $0\nu\beta\beta$ experiment will also need to be a highly efficient

[1] http://majorana.pnl.gov/

detector since the loss of any $\beta\beta$ events would be undesirable. The combination of an active source experiment and the short range of electrons in Ge metal greatly boosts $\beta\beta$ capture effiency. This short range also means that $\beta\beta$ events will be spatially localized as opposed to the majority of backgrounds which will tend to be more spatially extended (multiple Compton scattering γ rays from the 2615 keV line in the ^{232}Th decay chain are a prime example). Very low backgrounds near $Q_{\beta\beta}$ are also vitally important. At 2039 keV, ^{76}Ge has $Q_{\beta\beta}$ at a higher energy than many radioactive backgrounds. Furthermore, Ge diode detectors are intrinsically low-background because their nature as semiconductor devices means that they will have very little contamination from dust and the U and Th backgrounds it brings.

2. MAJORANA PROJECT OVERVIEW

Majorana is envisioned as a scalable experiment, consisting of several detector modules containing 57, roughly 1 kg Ge detectors on sliding shielding towers. Each module will hold 19 strings of three detectors in a hexagonal close-packed configuration hanging from an electroformed copper cold plate. The 100 meV neutrino mass sensitivity goal corresponds to a $0\nu\beta\beta$ lifetime of roughly 10^{26} years. This sensitivity is ultimately limited by signal to background ratio, leading to a background goal for the Majorana project. We hope to demonstrate a background of roughly one count per tonne of Ge per year in our 4 keV region of interest. There are two main background reduction strategies for the Majorana project: one taking place during construction of the experiment, and the other while collecting and analyzing data. During the construction phase, we plan to lower backgrounds by: producing and selecting ultra-clean materials, minimizing the amount of non-source material in the array, using clean passive shielding, and locating the experiment at a deep site to reduce cosmic rays and related induced activity. While running the experiment and analyzing data, we plan to separate background from signal events by: using active veto shielding to eliminate events originating outside the shield and combining segmentation, pulse shape analysis, detector-to-detector anti-coincidence and time correlation cuts.

3. READINESS AND R&D

The Majorana collaboration has recently made a great deal of progress on both experimental test bench and Monte Carlo studies. These have focused on demonstrating the efficacy of our background reduction techniques and the overall feasibility of our experimental design. We have developed a Monte Carlo framework called MaGe in cooperation with the GERDA collaboration[5]. Based mostly on the GEANT4 framework, MaGe has been verified against a variety of detectors and underground laboratory data. Another important step forward has been the demonstration of assay capabilities for ^{232}Th in electroformed copper parts. Background requirements for the Majorana project demand materials with and assay sensitivity to ^{232}Th impurities at the level of 1 μBq/kg. There are two main assay efforts: direct radiometric counting and "Inductively-Coupled Plasma Mass Spectroscopy" (ICPMS). The direct counting capabilities of the Majorana collaboration are centered at several of low-background counting facilities, and can detect ^{232}Th at the 8 μBq/kg level. Sensitivity is currently limited by sample size constraints and is largely irreducible. ICPMS can currently detect 2-4 μBq/kg of ^{232}Th, and is currently limited by reagent cleanliness (this is currently being addressed, making ICPMS a promising technique for reaching the assay goal). The Majorana collaboration has also demonstrated the efficacy of combining pulse shape analysis and detector segmentation for rejecting backgrounds. These efforts have largely revolved around the clover detector (a close-packed array of four 800 g Ge detectors in a single cryostat[6]) at LANL, and the 4x8 segmented detector at Michigan State University[7]. The clover detector work is detailed in reference [8]. Because the Majorana project will have 57 tightly packed detectors in the same cryostat, the use of a simple detector to detector anti-coincidence cut can greatly reject background events. The efficacy of this cut and others is detailed in [9].

4. CONCLUSIONS

The Majorana project design has been tailored specifically to the goals of the APS neutrino study[10]. As a scalable experiment, based on proven, existing technology, it is "ready to go." All Majorana R&D efforts focus on refining design details rather than on proof of principle. Majorana is the logical extension from the previous generation of ^{76}Ge $\beta\beta$ experiments, improving upon them by: fielding an order of magnitude more ^{76}Ge, lowering the background by roughly an order of magnitude, and incorporating detector design and electronics improvements leading to roughly thirty times better background rejection. The Majorana collaboration has also formed a large, experienced collaboration with the necessary experience and knowledge base for this experiment.

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